Check for updates

Responses of Tropical and Subtropical Plants to Air Pollution

7

Arideep Mukherjee, Bhanu Pandey, S. B. Agrawal, and Madhoolika Agrawal

Abstract

The tropical and subtropical regions of the world are facing strong negative effects of globalization, weakening the critical balance between ecosystem stability and socioeconomic development. Apart from increasing pressures of global climate change, deforestation, and shifts in land use pattern, air pollution is emerging as one of the major factors influencing ecosystem structure and function. Issues related to health, agricultural production, and economic losses due to air pollution in the tropical and subtropical regions are well known; however, information on air pollution-related effects on the tropical vegetation is limited. Therefore, based on the current literature, the status of air pollution and its effects on vegetation in the tropical and subtropical regions of the globe are explored in this chapter to understand the current scenario and to identify the knowledge gaps. Spatial and temporal variations were detected among different regions for particulate matter, its constituents, and gaseous pollutants including identification of the factors and sources influencing the air quality. Air pollution impacts were assessed based on changes in ecosystem structure and functions such as the patterns of biodiversity change, alteration in litterfall and decomposition, the response of leaf functional traits, and bioaccumulation in the community or individual plant species. Air pollution significantly influenced major ecological processes such as litterfall, decomposition, and plant diversity indirectly through changes in soil quality as well as through a direct effect on growth and physiol-

A. Mukherjee · S. B. Agrawal · M. Agrawal (✉)
Laboratory of Air Pollution and Global Climate Change, Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India
e-mail: madhoo.agrawal@gmail.com

B. Pandey
Natural Resources and Environmental Management, CSIR-Central Institute of Mining & Fuel Research, Dhanbad, Jharkhand, India

S. C. Garkoti et al. (eds.), *Tropical Ecosystems: Structure, Functions and Challenges in the Face of Global Change*,
https://doi.org/10.1007/978-981-13-8249-9_7

ogy of native plants. Plants respond to changes in air quality through alternation in growth and morphology, physiological plasticity, and modifying leaf functional traits. These responses are both species- and pollutant-specific, as not all species responded equally to air pollution. Bioaccumulation pattern also showed a distinct relationship between pollutant accumulation and species specificity.

Keywords
Tropics · Air quality · Forest · Urban · Tree · Vegetation

7.1 Introduction

Ecosystem dynamics is regulated by different biotic and abiotic factors. The balance between these factors is the key for maintaining ecosystem structure and function. Climate change along with changing land use pattern has significantly altered this balance in recent times. Air pollution considerably adds to already existing stress and further influences the environment. Compared to other stresses, air pollution impacts are both local and regional and are directly toxic to plants and animals (Mukherjee and Agrawal 2017a). Air quality influences vegetation by altering species composition and structure (Koch et al. 2016; Pandey et al. 2014), rate of decomposition (Ferreira et al. 2017), growth and morphology (Moraes et al. 2003; Mukherjee and Agrawal 2016), physiological processes (Baek and Woo 2010), leaf functional traits (Baek and Woo 2010; Moraes et al. 2002; Mukherjee and Agrawal 2016), and foliar bioaccumulation of toxic chemicals (Nakazato et al. 2016; Breulmann et al. 2002).

The tropics surround the Earth's equator within the latitudes of Tropics of Cancer and Capricorn at ±23.5°. These latitudes relate to the axial tilt of the Earth; in all areas between them, the sun reaches a point directly overhead at least once during the solar year. Although topography and other factors mostly contribute to local climatic variations, the tropical regions are typically warm and experience little seasonal changes in daily temperatures. Important features of the tropics are the prevalence of rain in the moist regions near the equator and increasing seasonality of rainfall with distance from the equator. The tropics are the biologically richest ecosystems on the Earth (Laurance et al. 2012). A significant proportion of this diversity is already under threat, which is most likely to amplify due to the current rate of climate change. Changes in climate are likely to have a greater impact in the tropics than elsewhere because many species are specialized to deal with a narrow range of environmental conditions. Species in the tropics are not as able to tolerate changes in climate as those accustomed to more significant changes in seasonal conditions in other parts of the world.

Emissions of sulfur and nitrogen-related compounds into the atmosphere over industrialized regions in Europe, North America, and Asia have strongly affected the climatic conditions within and around these regions throughout the twentieth century (Qu et al. 2016). The present fluxes of sulfur (SO_2, SO_4^{2-}) and nitrogen

(NOx, NO_3^-, NH_3, NH_4^+) to the atmosphere are much larger than the estimated natural fluxes (Seinfeld and Pandis 2016). These large-scale perturbations have resulted in significant adverse effects on the environment. The detrimental effects include widespread acidification of the Earth's surface and groundwaters with associated biological consequences, acidification of soils, increased rate of corrosion of buildings and monuments, and formation of secondary air pollutants, such as ozone (O_3), that are toxic to all life forms (Tian and Niu 2015). Such changes may occur as a result of biological and geological processes, short-term climatic fluctuations, or volcanic eruptions or by anthropogenic activities such as emissions of air pollutants in the atmosphere from vehicles and industries.

In most of the tropical countries, particulate matter (PM) and O_3 have been identified as major air pollutants due to increasing number of vehicles and biomass burning activities (Beig and Singh 2007; Cooper et al. 2014; Mukherjee and Agrawal 2017b). Historical trends have shown a decline in PM in most regions of the world, but levels are still critical in most of the tropical countries (Mukherjee and Agrawal 2017b; WHO 2016). A positive significant increment of 7–9% in tropospheric columnar O_3 per decade has been recorded across the tropical South Atlantic, India, Southeast Asia, and the tropical/subtropical regions downwind of China (Beig and Singh 2007).

Dey et al. (2012) recorded an increase in $PM_{2.5}$ (particles 2.5 μm or less in size) levels by more than 15 $\mu g\ m^{-3}$ from 2000 to 2010 in most parts of central, northern, and eastern India and northern Bangladesh. Gurjar et al. (2016) found decreasing trend in sulfur dioxide (SO_2) levels in most of the megacities in India, whereas opposite trend was observed in the case of nitrogen oxide (NOx). Heue et al. (2016) found an increase in tropical tropospheric column O_3 by 0.70 DU decade^{-1} or 0.35% year^{-1} from 1995 to 2015. As pollutant concentrations have significantly increased in most of the tropical regions, the responses of plants to ambient air quality have also changed (Pandey et al. 1992; Mukherjee and Agrawal 2018). Improvements in tools and techniques have considerably improved our knowledge of plant response with the addition of environmental modelling and geographical information system (Sicard et al. 2016). Recent reports have observed wide variations in pollution response in different species which are due to long-term evolutionary adaptation as well as due to increase in local stress factors. Bioaccumulation studies have also shown a linear relationship between pollution concentration and bioaccumulation in recent times (Mukherjee et al. 2016). Major shifts in biodiversity pattern have also caused large-scale variations in individual plants as well as in community patterns (Narayan et al. 1994; Pandey et al. 2014).

Evaluation of responses of the tropical plants to air pollution becomes more important due to modifying effects of climatic conditions on air quality and the tropics being biologically richest ecosystems already suffering from different natural and anthropogenic threats. The present chapter describes air quality status, sources of air pollution, factors influencing air quality in the tropics, and the responses of vegetation to air pollutants in different tropical regions.

7.2 Methodology

A systematic survey was first performed in World Wide Web with keywords such as air pollution, particulate matter, air pollution sources, plant responses, biodiversity, ecosystem functions, decomposition, and leaf traits with specific filters such as tropics, subtropics, tropical forest, tropical grassland, and tropical biodiversity in PubMed, Web of Science, Google Scholar, ScienceDirect, and Springer Link. Among the articles found, only those satisfying the criteria such as sound methodology, spatial-temporal variabilities, and large dataset were screened for further analysis. Papers for the first section of the article of air quality were screened which were specifically performed under a tropical or subtropical environment of Southeast Asia; West, East, and Central Africa; and South and part of North America (Mexico) in urban, suburban, and rural environments with relevant sampling protocols and large sample size. For assessment of responses of the tropical and subtropical plants to air pollution, papers were further screened for different response types such as foliar bioaccumulation, leaf functional traits, physiology, growth and morphology, biodiversity, litterfall and decomposition, and toxicity symptoms for trees, lichens, grasses, shrubs, and crop plants.

7.3 Air Quality in the Tropics

Pollution of air and water by anthropogenic activities is a noticeable feature of urban and industrial systems throughout the tropical regions. The airborne pollutants that are of major concern in these regions include toxic atmospheric gases such as SO_2, NOx, volatile organic compounds (VOCs), O_3, and carbon monoxide (CO); PM and its components such as polycyclic aromatic hydrocarbons (PAHs) and black carbon (BC); toxic elements such as lead (Pb) and fluoride (F); photochemical oxidants; and acid deposition. Most of the airborne substances are primary pollutants released directly from stationary and mobile sources, whereas secondary pollutants are formed in the atmosphere by chemical transformation of primary pollutants.

These airborne particles, gases, and their reaction products are carried out by winds and clouds to different directions in distant places and thereafter get deposited in various forms of gases, fine and coarse particles, or as dissolved or suspended substances in precipitation. These deposition processes transport the airborne chemicals to the surfaces of vegetation, soil, surface water, buildings, and cultural resources at short or long distances from the original emission sources. The direct and indirect effects of air pollution have been summarized in Fig. 7.1. SO_2 and NOx both directly and indirectly influence human health, vegetation, and soil. The direct effects are ill health, damage to plant surface, and degradation of environmental quality. These depend upon the concentration of pollutants and decline sharply with increasing distances from emission sources. Thus, the direct effects are more of a local in nature with a geographical extent of few kilometers.

Fig. 7.1 Schematic diagram showing sources and factors influencing air pollution and its impact on different ecological processes

7.3.1 Particulate Matter

Based on PM_{10} (particles 10 μm or less in size) and $PM_{2.5}$ data of the WHO (World Health Organization) for the tropical countries (WHO 2016), Asian countries were found to be highly polluted with PM_{10} values above 100 μg m^{-3} in India and Bangladesh while above the mean annual WHO standard of 20 μg m^{-3} in the Philippines, Malaysia, Sri Lanka, Bhutan, and Indonesia. Among Asian countries, Singapore showed the least PM_{10} value of 30 μg m^{-3} (Fig. 7.2). Higher values were also recorded in African countries although data of only a few countries were available. PM_{10} values in all the African countries were above the WHO standard. Compared to Asian and African countries, PM_{10} values were reasonably lower in countries of South America. PM_{10} concentration was 33.78 μg m^{-3} in Brazil, whereas in Colombia and Ecuador values were, respectively, 39.85 and 35.82 μg m^{-3}. In Central and North American countries, PM_{10} values were above the WHO annual standard in Mexico (56.14 μg m^{-3}), Costa Rica (28.96 μg m^{-3}), and Panama (31.1 μg m^{-3}). Among the tropical cities, PM_{10} value was the highest in the Indian city of Gwalior (329 μg m^{-3}) followed by Allahabad (317 μg m^{-3}), Raipur (268 μg m^{-3}), and Delhi (229 μg m^{-3}). Among other cities, PM_{10} value (μg m^{-3}) was 170 in Kampala, the capital city of Uganda; 169.7 and 158.05, respectively, in Sylhet and Dhaka, Bangladesh; and 141 in Bamenda, Cameroon. Cities like Tezpur, India (11 μg m^{-3}); Madre de Deuss, Brazil (12 μg m^{-3}); and Pasto, Colombia (18 μg m^{-3}), showed lower values for PM_{10} (WHO 2016). In São Paulo, Rio de Janeiro, and Piracicaba, Brazil, and in Bogotá, the capital of Colombia, PM_{10} levels were above the WHO standard (Mukherjee and Agrawal 2017b). Exceedances in PM levels above the WHO standard were more frequent in African cities like Accra, Ghana, and Bamenda, Bafoussam, and Yaounde, Cameroon,

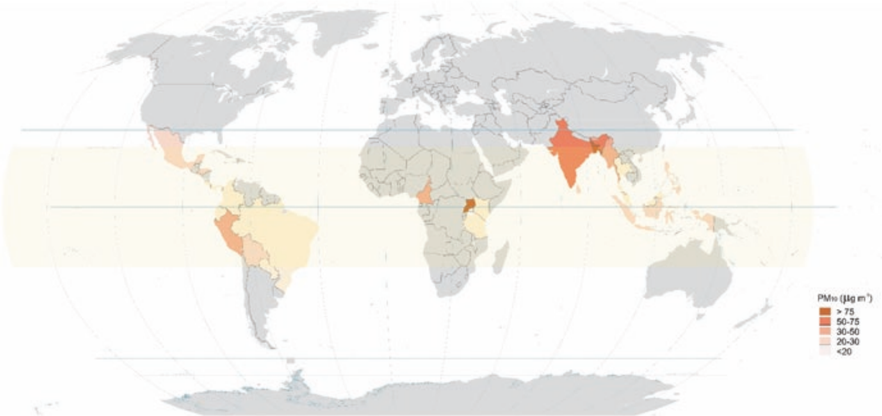

Fig. 7.2 Spatial variations in PM_{10} concentrations in different tropical countries, and shaded area represents the distribution of the tropical region

due to both natural and anthropogenic sources (Mukherjee and Agrawal 2017b). Mukherjee and Agrawal (2017b) reviewed the global status of PM_{10} and reported higher values in the tropical region compared to temperate regions of the world mostly attributed to increases in traffic and biomass burning in the tropics. The major reasons behind this trend are due to differences in the quality of vehicles and roads, density of roads, emission standard of engines, and strict regulation standards, apart from increase in vehicular density in developing countries. Although biomass burning is a traditional practice, its intensity and level have been tremendously increased in recent time due to strong economic pressure on farmers of developing countries lacking proper disposal plan of crop residues. Even in urban areas, biomass is frequently burned due to the lack of proper disposal facilities.

$PM_{2.5}$ levels showed the following trend: South Asia > Africa > Central America > North America > South America. For all the tropical countries, values were several times higher than the WHO annual limit of 10 μg m^{-3} (WHO 2016), indicating a severe problem of fine PM pollution in the tropics. $PM_{2.5}$ levels were above 50 μg m^{-3} in India, Bangladesh, Myanmar, and Cameroon (Fig. 7.3). Among the Indian cities, fine PM was maximum in Gwalior (176.14 μg m^{-3}) followed by Allahabad (169.72 μg m^{-3}), Patna (148.94 μg m^{-3}), Raipur (143.66 μg m^{-3}), and Delhi (122.10 μg m^{-3}) (WHO 2016). $PM_{2.5}$ value below the WHO annual mean standard was only recorded in 11 out of 294 cities or metropolitan areas in the world (WHO 2016). Mukherjee and Agrawal (2017a) also reported the critical condition of $PM_{2.5}$ in the Asian and African tropics. $PM_{2.5}$ levels in Dakar, Senegal; Nairobi, Kenya; and Dar es Salaam, Tanzania, were several times higher than the WHO standard.

In Delhi, the suspended particulate matter (SPM) and PM_{10} values have been continuously exceeding the standards in the last decade with a steep rise after 2005 (Gurjar et al. 2016). The observed trend is due to increased traffic load in the major cities in India. In Mumbai, SPM concentrations varied between the years with

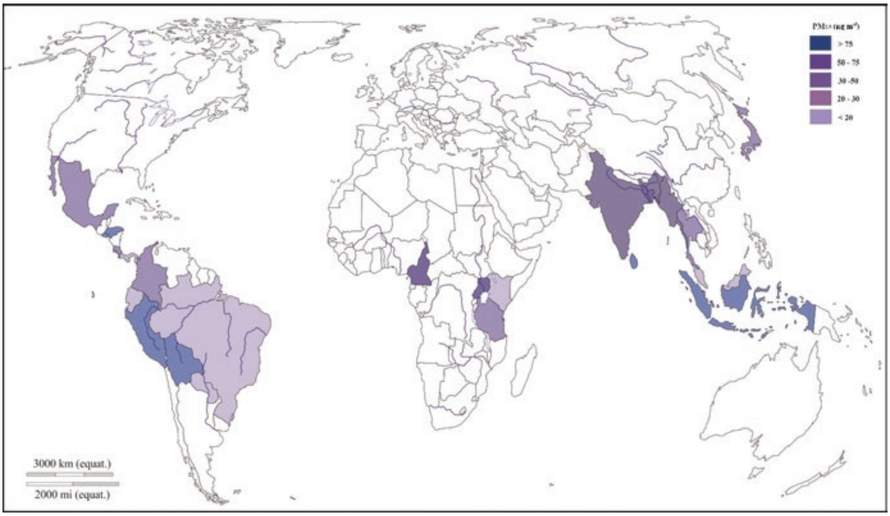

Fig. 7.3 Spatial variations in $PM_{2.5}$ concentrations in different tropical countries

increasing trend in concentrations from 2005 to 2012. SPM and PM_{10} emissions were higher in Kolkata compared to Mumbai and Delhi, whereas SPM concentration was maximum in Delhi followed by Kolkata and Mumbai (Gurjar et al. 2016). On comparison of SPM concentrations with earlier reports in Varanasi City, a clear trend of increment has been observed in the last two decades. At heavy traffic area, a 64% increase in SPM concentration was recorded during 2002–2012 (Trivedi and Agrawal 2003; Mukherjee and Agrawal 2016).

Sumit et al. (2012) assessed aerosol properties from different sites (Pune, Sinhgad, Ahmedabad, Trivandrum, and Gadanki) in India with the differences in urbanization, altitude, and land use. Aerosol optical depth, a marker of particulate matter pollution, varied from 0.23 to 0.67 between different sites, and values were significantly higher compared to reported values from Europe and the USA (<0.2) (Sumit et al. 2012; Provençal et al. 2017). Trivandrum site showed higher concentrations of small particles, whereas coarse PM was higher over Ahmedabad. The variations between different sites were mostly attributed to local emissions, meteorological conditions, and seasonal variations.

7.3.1.1 Composition of Particulate Matter

Polycyclic aromatic hydrocarbons (PAHs) are the products of fossil fuel combustion and are carcinogenic in nature (Ayi Fanou et al. 2006; Cavalcante et al. 2017). PAHs are mostly emitted from incomplete combustion of gasoline and diesel, crude oil, and organic materials. PAHs are weakly soluble in water and exist in atmosphere on the surface of particulate matter or in gaseous phase. Ayi Fanou et al. (2006) found significantly higher concentrations of benzene and PAHs associated with particulate matter in Cotonou, the largest tropical port city on the south coast of Benin in West Africa. Benzene and PAHs in ambient air were also found in the village of Cotonou, Benin, although concentrations were significantly lower than the values recorded in the city (Ayi Fanou et al. 2006). The total PAHs concentrations ranged from 1.73 to 2.83 ng m^{-3} in the metropolitan area of Fortaleza-CE, Brazil. High PAHs concentrations at the city center were correlated with the high vehicular flow (Cavalcante et al. 2017). Krauss et al. (2005) reported an average PAHs concentration of 35 ng m^{-3} in the tropical rainforest near Manaus, Brazil; however, the value was ten times lower than the nearby urban location. In the metropolitan area of Fortaleza-CE, Brazil, Cavalcante et al. (2017) reported that 62.93% variation in PAHs concentrations in PM was governed by constructed area and PAHs levels as well as PM concentrations, reduced with increasing tree cover.

In an urban area of Amritsar, Punjab, PAHs concentrations ranged from 37 to 274 ng m^{-3} due to higher biomass burning, coal combustion, and vehicular emissions, whereas concentrations were much lower with values ranging from 18.3 to 66.6 ng m^{-3} in Mumbai (Kaur et al. 2013; Sahu et al. 2008). As compared to Amritsar and Mumbai, significantly higher PAHs concentrations were recorded in Agra, India, and in Kandy, Sri Lanka (Masih et al. 2012; Wickramasinghe et al. 2011). As compared to Asian cities, values of PAHs were relatively lower in South American cities (Table 7.1).

Black carbon (BC) is formed due to incomplete combustion of fuel, biomass burning, and vehicular and industrial activities (Hung et al. 2014; Salako et al. 2012). Particle size of BC ranges from few nanometers to microns which are mostly measured in $PM_{2.5}$ range. The major portion of black carbon is made up of carbon (60%) with contribution of various aromatic compounds. Atmospheric lifetime of BC ranges from few days to weeks. BC is known for its strong radiative forcing with a stronger global warming potential than CO_2. BC levels showed significant spatial variations among the different tropical cities (Table 7.2). Higher values were recorded in Dhaka, Bangladesh, and Bangkok, Thailand, followed by Indian cities of New Delhi and Hyderabad. Values above 10 μg m^{-3} were recorded in Kathmandu (Nepal), Dakar (Senegal), and Hyderabad (India). Lower values of BC were recorded in Chihuahua and Tijuana, Mexico; Anantapur, India; and Kuala Lumpur, Malaysia (Table 7.2). Variations in BC concentrations depend upon sources and prevailing meteorological conditions (Salako et al. 2012).

Table 7.1 Spatial-temporal variations in PAHs concentrations in different locations/cities in different tropical countries

Location	Period	PAHs (ng m^{-3})	References
Agra, India	2006–2007	8.32–1036.79	Masih et al. (2012)
Amritsar, India	2011	37–274	Kaur et al. (2013)
Mumbai, India	–	18.3–66.6	Sahu et al. (2008)
Kandy, Sri Lanka	2008–2009	57.43–1246.12	Wickramasinghe et al. (2011)
Montenegro, Brazil	2004–2005	2.9–17.54	Pereira et al. (2013)
Porto Alegre, Brazil	2001–2002	0.04–2.30	Dallarosa et al. (2005)
São Paulo, Brazil	2003–2004	1.6–7.8	Vasconcellos et al. (2011)
Concepción, Chile	2007	26–230	Pozo et al. (2012)
Santiago, Chile	–	6.4	Romero et al. (2002)

Table 7.2 Spatial-temporal variations in black carbon concentrations in different locations/cities in different tropical countries

Location	Period	BC ($\mu g\ m^{-3}$)	References
Ahmedabad, India	2003–2005	3.25	Ramachandran and Rajesh (2007)
Anantapur, India	2010	3.03	Reddy et al. (2012b)
Hyderabad, India	2006	12	Badarinath et al. (2009)
Hyderabad, India	2010	6.73	Swamy et al. (2012)
Kanpur, India	2006–2007	0.03–10	Baxla et al. (2009)
Mumbai, India	2008	3.58	Salako et al. (2012)
New Delhi, India	2007	14	Tiwari et al. (2009)
Pune, India	2004–2005	5.05	Panicker et al. (2010)
Dhaka, Bangladesh	2010–2011	22.77	Begum et al. (2012)
Dhaka, Bangladesh	2010	36.57	Salako et al. (2012)
Kathmandu, Nepal	2009–2010	8.6	Sharma et al. (2012)
Southern Himalaya, Nepal	2006–2008	0.16	Marinoni et al. (2010)
Bangkok, Thailand	2007–2008	9.4	Salako et al. (2012)
Bangkok, Thailand	2010	25.5	Hung et al. (2014)
Pathum Thani, Thailand	2008	4.65	Salako et al. (2012)
Kuala Lumpur, Malaysia	2008	3.85	Salako et al. (2012)
Chihuahua, Mexico	2008	2.14	Raysoni et al. (2011)
Tijuana, Mexico	2010	1.65	Shores et al. (2013)
Dakar, Senegal	2008–2009	10.4	Doumbia et al. (2012)

N deposition has been identified as the third greatest driver of biodiversity loss after land use and climate change as it alters species richness, dominance, evenness, and abundance (Xiankai et al. 2008). The tropical and subtropical areas of the world share almost 40% of the global applications of N fertilizers (Xiankai et al. 2008). In an urban atmosphere of New Delhi, India, Gupta et al. (2016) observed 2.5 times higher dust fall deposition at polluted site compared to reference site with higher concentrations of calcium ion (Ca^{+2}) and sulfate (SO_4^{-2}). Around highly industrialized region in Sonbhadra district of India, Singh and Agrawal (2005) studied N deposition at eight sites in the leeward side of thermal power plants on a 30 km transect and recorded N deposition rate of 9.67 kg ha^{-1} $year^{-1}$ at the distantly situated site from industry and 26.35 kg ha^{-1} $year^{-1}$ at the heavily polluted site, indicating the role of industrial pollution in nitrogen deposition. In the same study, SO_4^{-2} and nitrate (NO_3^-) were recorded as the major anions in the atmospheric deposits.

7.3.2 Gaseous Air Pollutants

7.3.2.1 Primary Gaseous Pollutants

After the industrial revolution, problems of gaseous air pollutants have been realized in all the developing and developed nations. Typical meteorological factors, intensive burning, and poorly maintained and higher numbers of vehicles in the tropics have resulted in a significant load of gaseous pollutants.

VOCs are gaseous air pollutants with short- to long-term adverse health effects. VOCs are emitted from combustion of fuels such as oil, gasoline, coal, wood, and natural gas. VOCs have a high vapor pressure at normal temperature and with lower water solubility. NOx is a primary air pollutant formed during combustion of fuels by the oxidation of atmospheric nitrogen within the fuel at high temperature. NOx denote the total concentrations of NO and NO_2 which are interconvertible in the presence of sunlight and other atmospheric gases especially O_3. Traffic is known to be the most significant source of NOx. SO_2 is a colorless, water-soluble gas formed by combustion of coal and oil. SO_2 is considered as one of the major harmful gases to plants as well as to public health. Major sources of SO_2 are coal-fired power plants and industries. CO is a colorless and odorless gas which is produced by the incomplete combustion of fossil fuels. Major sources of ambient CO are vehicular emissions and biomass burning.

Baumbach et al. (1995) found very high concentrations of VOCs and NOx in the large tropical West African city of Lagos, Nigeria, whereas average half-hour value of benzene was 250 pg m^{-3}. CO/NOx ratio was found to be 150–200 times higher than the previous reports in European cities (Baumbach et al. 1995). Valdés Manzanilla and de la Cruz Uc (2015) assessed spatial variability in SO_2 concentration in the tropical city of Villahermosa, Mexico, and found 363.2 tons of SO_2 emission in the metropolitan zone and the intersections of main roads in the city showed maximum concentrations of $SO_{2.}$

Dionisio et al. (2010) reported high CO concentrations in Accra, Ghana, which is mainly generated through vehicular combustion and biomass burning. CO levels were significantly lower in São Paulo, Brazil, compared to Accra. Azmi et al. (2010) found a correlation between traffic load and CO levels in Klang Valley, Malaysia. Awang et al. (2016) also recorded higher values of CO in three port cities in Malaysia. The industrial site showed maximum CO concentrations of 334 μg m^{-3}, whereas the lowest value of 42 μg m^{-3} was recorded at the semi-urban area in Dhaka, Bangladesh (Salam et al. 2008) (Table 7.3). Higher concentrations of CO around the industrial site are mainly due to incomplete combustion of fuels during industrial activities (Salam et al. 2008).

Gurjar et al. (2016) observed decreasing trend of SO_2 in all three megacities of India due to a decrease in the content of sulfur in coal and diesel, whereas increasing trend for NOx was attributed to increasing number of vehicles. Among major Indian cities, SO_2 emission was maximum in Mumbai followed by Delhi and Kolkata (Gurjar et al. 2016). Mukherjee and Agrawal (2016) also observed higher concentrations of NO_2 in different zones of Varanasi City, whereas the level of SO_2 was well below the NAAQS (CPCB 2009) of 50 μg m^{-3}. There is a remarkable reduction in SO_2 concentration in Varanasi City during the past 10 years, whereas NO_2 concentration has significantly increased by 25.6–72.2% in the last two decades (Pandey et al. 1992; Trivedi and Agrawal 2003; Mukherjee and Agrawal 2016). Both SO_2 and NO_2 concentrations were recorded below NAAQS of India in two tropical coastal cities in India (Guttikunda et al. 2015).

Table 7.3 Spatial-temporal variations in different gaseous air pollutant concentrations in different tropical countries

Location	Period	SO_2 (μg m^{-3})	O_3 (ppb)	NO_2 (μg m^{-3})	CO (ppm)	References
Agra, India	1999–2001	3.8		7		Kumar et al. (2004)
Anantapur, India	2010		20.35	23.948		Reddy et al.(2012a)
Chennai, India	2011–2012	10.85		20		Guttikunda et al. (2015)
Delhi, India	2005–2009	7.729		51.55		Mallik and Lal (2014)
Delhi, India	2013–2014		30.45			Kumar et al. (2015)
Durgapur, India	2005–2009	8.174		59.16		Mallik and Lal (2014)
Guwahati, India	2005–2009	7.074		16.28		Mallik and Lal (2014)
Hyderabad, India	2009		21			Yerramsetti et al. (2013)
Hyderabad, India	2010		14.33			Swamy et al. (2012)
Jodhpur, India	2005–2009	6.55		22.18		Mallik and Lal (2014)
Kannur, India	2009–2010		1.6–15.15			Nishanth et al. (2012)
Kolkata, India	2005–2009	10.79		58.14		Mallik and Lal (2014)
Nagpur, India	2005–2009	9.458		30.19		Mallik and Lal (2014)
Visakhapatnam, India	2011–2012	16.75		18.45		Guttikunda et al. (2015)
Dhaka, Bangladesh	2006	48.3	13.95	21.0	0.126	Salam et al. (2008)
Klang Valley, Malaysia	1997–2006	15.72	16.6	43.24	1.269	Azmi et al. (2010)
Klang, Malaysia	2009	10.48	20.3	38.16	0.952	Awang et al. (2016)
Pasir Gudang, Malaysia	2009	11.79	14.4	25.00	0.619	Awang et al. (2016)
Perai, Malaysia	2009	5.764	15.4	22.56	0.706	Awang et al. (2016)
São Paulo, Brazil	2000–2007	13.20	66	56.97	7.63	Rodrigues-Silva et al. (2012)
Santa Clara, Cuba	2010	5.95		11.35		Alejo et al. (2013)
Chihuahua, Mexico	2008			42.86		Raysoni et al. (2011)
Accra, Ghana	2006–2008				7–55	Dionisio et al. (2010)
Dar es Salaam, Tanzania	2005–2007	4.6	11.75	11.95		Mmari et al. (2013)

NO_2 concentrations were two times higher at semi-urban and coastal sites compared to a rural site, whereas SO_2 concentration was maximum at a semi-urban site (5.1 μg m^{-3}) and lowest at a rural site (0.94 μg m^{-3}) in and near Dar es Salaam, Tanzania (Mmari et al. 2013). In Dhaka, the average concentrations of SO_2 and NO_2 were much lower than the WHO standards. The highest concentration of NO_2 (40 μg m^{-3}) was found at a traffic site, whereas the highest SO_2 concentration of 76.8 μg m^{-3} was found in the commercial and heavy traffic areas (Salam et al. 2008) (Table 7.3).

VOCs are major precursors for O_3 formation. Apart from traffic and combustion sources, biogenic sources of VOCs also play a major role in O_3 formation in both urban and forested areas in the tropics. Singh et al. (2014) estimated VOCs (isoprene and monoterpene) emission potential of 60 common plant species in the Vidarbha region of Maharashtra and found maximum VOC emission rate of 75.2 g g^{-1} h^{-1} in *Dalbergia sissoo*, whereas maximum O_3-forming potential was observed in *Mangifera indica* (77 g O_3 $tree^{-1}$ day^{-1}). The study further found higher O_3-forming potential in 16 out of 60 species. Maximum monoterpene and isoprene emission rates were in *Murraya koenigii* and *D. sissoo*, respectively (Singh et al. 2014).

7.3.2.2 Secondary Gaseous Pollutants

Tropospheric O_3 is a secondary air pollutant, which is important from both atmospheric and biological perspectives. Tropospheric O_3 is a blue color gas, with a strong irritating smell formed by photochemical reactions of NOx, CO, and VOCs. O_3 concentration in the atmosphere is regulated by its precursor concentrations (hydrocarbons, CO, NOx) which are mostly emitted from combustion of fossil fuel, biomass burning, and industrial emissions and from natural sources such as lightning and microbial activity in soil. O_3 influences the oxidation capacity of the atmosphere since O_3 itself acts as a primary reactant and also due to its ability to produce hydroxyl radicals after photolysis, which play a very crucial role in the cycling of other trace gases in the atmosphere. O_3 injury in plants has been regularly reported from many areas of the tropical and temperate regions and on regional scales in North America and Europe.

Surface O_3 levels vary from 15 to 53 ppb in different tropical cities of India (Yerramsetti et al. 2013). O_3 levels were below the national and WHO standards in three port cities in Malaysia. NOx, CO, and meteorological conditions are identified as major factors behind diurnal variations in surface O_3 concentrations (Awang et al. 2016). Kumar et al. (2015) also reported O_3 concentrations below the national and WHO standards in the urban background, urban/traffic, and rural areas in Delhi-NCR, whereas concentrations were higher than both the Brazilian and WHO standards in São Paulo, Brazil (Rodrigues-Silva et al. 2012). Among the monitoring sites in Delhi-NCR, higher concentrations were observed at rural site followed by urban background and urban traffic site (Kumar et al. 2015). In an urban tropical site of Belo Horizonte, Brazil, O_3 concentrations varied from 8.7 to 96.1 ppb with an average of 38.17 ppb. Mmari et al. (2013) also reported higher O_3 concentrations at rural and coastal sites compared to a semi-urban site near Dar es Salaam, Tanzania.

Yerramsetti et al. (2013) found a role of the nocturnal chemistry of NOx in the formation of O_3 during daytime at a tropical urban site in Hyderabad (Table 7.3).

7.4 Factors Influencing Air Quality in the Tropics

7.4.1 Meteorological Factors

Air quality in the tropics is largely governed by meteorological factors apart from anthropogenic emissions. Major influencing factors that regulate spatial-temporal variations in the tropics are changing atmospheric dispersion conditions (wind direction, wind speed, atmospheric stability, relative humidity, and height of boundary layer) (Baumbach et al. 1995; Ferreira et al. 2017; Mukherjee and Agrawal 2017b; Reddy et al. 2012a). Gurjar et al. (2016) reported higher SO_2 concentrations in winter season followed by post-monsoon, pre-monsoon, and monsoon over Delhi, Mumbai, and Kolkata. PM_{10} and lead (Pb) levels were also lowered during monsoon season. In Mumbai, monthly mean SPM level also showed considerable reduction during the monsoon period from June to October (Gurjar et al. 2016). Long-term air pollution data in three Indian megacities showed ambient temperature, relative humidity, wind speed, and rainfall as the major determining meteorological variables influencing air quality. High humidity, precipitation, temperature, and light intensity have been reported to influence uptake rates and interactions of different chemical elements in tropical forests (Breulmann et al. 2002). Severe El Niño and quasi-El Niño are also responsible for forest fires in Indonesia, resulting in severe air pollution in the region (Hayasaka et al. 2014).

Among the gaseous air pollutants, surface O_3 concentration is mostly affected by meteorological factors apart from primary sources of O_3. Solar elevation, clouds, and aerosols along with temperature affect the photolysis and atmospheric reactions involved in the generation of O_3 (Silva and Tomaz 2013). Seasonal variations with the highest O_3 in the summer months and lowest during the rainy season are distinct throughout the tropical region, which are mainly due to higher temperature with long sunshine hours in summer providing an ideal condition for O_3 formation (Silva and Tomaz 2013). Nishanth et al. (2012) found positive correlation between O_3 and different meteorological variables such as solar radiation (0.91) and temperature (0.81) and negative correlation with relative humidity (0.88) and wind speed (0.77), indicating the role of meteorological factors in regulating surface O_3 concentrations at a tropical coastal site (Kannur) in India.

Boundary layer height (the lowermost part of the troposphere where the surface of the Earth interacts with the large-scale atmospheric flow) is one of the major factors influencing air pollutant concentrations in the tropical atmosphere. Reddy et al. (2012a) reported the influence of boundary layer dynamics in surface O_3 concentrations at a tropical rural site in the southern part of India. In tropics, daytime temperature and sunlight intensity are generally high all year round. The intensive sunlight intensifies photochemical processes in the atmosphere, resulting in the generation of high concentration of hydroxyl radicals (Crutzen and Giedel 1983). In large parts of the tropics, average rainfall rates are high at least during the rainy season. Therefore, wet deposition is likely to be the major deposition mechanism, but in the regions where precipitation rates are low, wet deposition processes are not significant. More studies related to atmospheric chemistry in the tropics are needed to understand both dry and wet deposition patterns with seasonal variations.

7.4.2 Sources

Air pollutants are emitted from a wide variety of sources. For air pollution control and mitigation, it is foremost important to identify and understand the nature of sources and factors responsible for regulating these sources. Baumbach et al. (1995) reported major sources of air pollution such as traffic (passenger cars and utility vehicles), industries (oil refineries with their area sources, gas flares, and electrical power stations), biomass burning (for cooking purposes and uncontrolled waste burning), and dust from Sahara Desert in large tropical West African city of Lagos, Nigeria. In the tropical city of Villahermosa, Mexico, Valdés Manzanilla and de la Cruz Uc (2015) identified mobile sources as the major sources of SO_2 pollution in the city. Among the mobile sources, trucks followed by public transportation vehicles were identified for higher emissions of SO_2.

Gurjar et al. (2016) identified industries and power plants as major sources of SPM and PM_{10} emissions (20–80%) among the anthropogenic sources in three megacities of India. Other important sources of SPM and PM_{10} in India are small-scale industries, transportation, construction, resuspended soil and road dust, domestic coal burning, and biomass burning (Gurjar et al. 2016). Coal combustion is one of the major sources of PM and NOx in Indian cities, whereas oil combustion is the predominant source of SO_2 (Gurjar et al. 2016). SO_2 concentration in various cities of India has drastically reduced with improvement in fuel quality and strict policies (Gurjar et al. 2016). The transportation sector is one of the major sources of NOx pollution in India contributing almost 50–70% of the total emission followed by industries (10–30%) (Gurjar et al. 2016).

Cavalcante et al. (2017) found light-duty vehicles as the most important emission source of PAHs in particulate matter followed by industrial activities (asphalt and steel production), combustion of wood and coal, and paved road dust in the metropolitan area of Fortaleza-CE, Brazil. Biomass or fossil fuel combustion was identified as the major source of atmospheric PAHs in a tropical rainforest near Manaus, Brazil (Krauss et al. 2005).

In Indo-Gangetic Plain, air pollution is heavily contributed by two-wheelers with two-stroke engines, and pollutants from vehicles are released at a very low height causing heavy pollution at the ground surface, which even gets worse with buildings around the roads that prevent dispersion of pollutants (Verma and Singh 2006). In two tropical coastal cities of Chennai and Visakhapatnam in India, Guttikunda et al. (2015) recorded vehicle exhaust accounting almost 60% and 43% of NOx emission, respectively. Further, 59%, 27%, and 5% contributions of the power plant, industries, and brick kilns, respectively, were calculated for total SO_2 emissions in

Chennai. The sources of O_3 precursors include vehicles and combustion of fossil fuels and biomass as well as natural processes such as NOx production by lightning and VOCs production by the tropical vegetation.

7.4.3 Forest Fire

With increasing human influence and overexploitation of forest resources and rise in temperature with uneven rainfall pattern due to climate change, there is a significant increase in the incidences of forest fires globally (Herawati and Santoso 2011; Le et al. 2014). The number of fire incidence in Vietnam was staggering with 16,086 fires per year during 2004–2012 (Le et al. 2014). Factors such as biomass accumulation, warmer and drier weather conditions, and anthropogenic influences in the tropical forests increase the fire incidences causing loss of biodiversity, degradation of natural habitat, reduction in natural decomposition process, and most importantly release of toxic atmospheric gases in large quantities causing severe air pollution in the tropics (Herawati and Santoso 2011). Le et al. (2014) identified several sources of forest fires in Vietnam such as the burning of crop residues, fire used by local people for hunting wild animals, use of smoke for honey collection, overexploitation of forest products, and trading conflicts for forest resources.

Peat fires are one of the major causes of air pollution in Central Kalimantan, Indonesia, causing a significant rise in PM and other gaseous pollutants during fire events. PM_{10} during fire events reached to a maximum value of 1905 μg m^{-3}, whereas NO_2 concentration averaged 30.5 μg m^{-3}, which was almost 2.24 times higher than in non-fire season. Similarly, SO_2 concentration reached 17.16 times higher during fire compared to non-fire season (Hayasaka et al. 2014).

Chir pine or blue pine (*Pinus roxburghii* Sarg) forests located between 1000 and 1800 m altitude in the Himalayan region are also prone to forest fire with incidences of 3908 fire per $year^{-1}$ (Vadrevu et al. 2012). Vadrevu et al. (2012) estimated total BC emissions of 431 Mg $year^{-1}$ from Himalayan region. Based on fire emission inventory by Heil et al. (2007), 55 teragram (Tg) of PM and 1098 Tg of carbon were estimated to be released during 1997 Indonesian vegetation fire. Sukitpaneenit and Kim Oanh (2014) also recorded increases in CO and PM_{10} levels during the events of forest fire in Northern Thailand.

7.5 Air Pollution Impacts on Ecosystem Structure and Function

The diversity of the tropical ecosystems and possible site-specificity together with limited resources for researching environmental problems in most tropical countries hinder better understanding of the problems. Airborne pollutants can affect ecosystems in two major ways: (1) by direct toxicity and (2) indirectly by changing soil nutrient availability. Present knowledge of each of these mechanisms is discussed below.

7.5.1 Direct Toxicity and Other Injurious Effects

Dust particles, aerosols, and other air pollutants are directly adsorbed on the large leaf surfaces of forest vegetation which ultimately influence plant function and structure (Breulmann et al. 2002). The deposition of particulate matter on the leaf surface causes blockage of solar radiation by shadowing the leaf surface, altering the pigment synthesis and the photosynthetic rate (Pereira et al. 2009). Air pollutant-stressed plants are more vulnerable to pest and fungal attack. In highly industrialized areas of Brazil, Moreira-Nordemann et al. (1988) observed damage to surrounding vegetation, but the direct effects of acidification cannot be adequately separated from those of gaseous pollutants.

Air pollutants such as SO_2, O_3, fluorides, and peroxyacyl nitrate (PAN) damage the leaves of plants. Chronic injury occurs on exposure of plants to low concentration of SO_2 at which the rate of accumulation of the ion is slow. The cells oxidize the sulfite ions and injury does not occur until sufficient sulfate ions get accumulated. This type of chronic injury is characterized by a general chlorotic appearance of the leaves. Cells are not directly harmed, but the chlorophyll is bleached which appears as a mild chlorosis or yellowing of the leaf or a silvering or bronzing of the lower leaf surface without necrosis (Agrawal and Agrawal 1999). Brownish necrotic streaks confined to the middle and upper laminar regions on *Panicum miliaceum* plant leaves were observed after 8 days of exposure with 0.5 ppm SO_2 (Agrawal et al. 1983). Shaw et al. (1993) reported the development of needle necrosis in Scots pine (*Pinus sylvestris* L.) due to SO_2 exposure of 34–58 μg m^{-3}. The acute injury was, however, resulted due to absorption of lethal quantities of SO_2 as full grayish green water-soaked areas which later converted as marginal or intercostal areas of dead tissues. In most plant species, these injuries develop as bleached areas, which upon drying or becoming dead or necrotic areas fall out leaving a ragged appearance to the leaf. In case of severe injury, abscission layer develops at the base of the petiole causing premature fall of the leaves (Mudd 2012). Pandey and Agrawal (1994) also recorded leaf injury symptoms in the form of bifacial chlorosis and necrosis mainly toward the tip and margin of the leaves in three tropical trees exposed to urban air pollution. Fluoride damages the edges of plants as brown or black pigmentation (Klumpp et al. 1996). Peroxyacyl nitrate causes a condition known as a silver leaf, in which the underside of the leaves turns silvery white or bronze (Oka et al. 2004).

As a strong oxidant, O_3 causes several types of symptoms including chlorosis and necrosis. The common symptoms associated with O_3 exposure include flecks (tiny light-tan irregular spots less than 1 mm diameter), stipples (small darkly pigmented areas approximately 2–4 mm diameter), bronzing, and reddening. O_3 damage on leaves appears as mottled spots which may be yellow, black, or brown. If the damage by O_3 is severe enough, the plant drops its leaves altogether. The reddish-brown stipples that develop on the leaves are the result of accumulation of black or red pigments in dead cells of the palisade tissue (Cho et al. 2011). Sanders et al. (1992) have also observed damaged chloroplast membranes, plasmalemma, and tonoplasts as a result of O_3 exposure. Swelling of thylakoid membranes leading to the breakdown of chloroplast integrity was shown to be the result of O_3 exposure (Crang and McQuattie 1986). Chaudhary and Agrawal (2014) also recorded O_3-induced visible foliar injury symptoms as small pale yellow and brown flecks on clover (*Trifolium alexandrinum*).

7.5.2 Changing Acidity of the Tropical Soils

Air pollution can cause severe acidity to soil due to the presence of acidic ions (Tian and Niu 2015). In the acidic soil, aluminum (Al) dominates the exchange complex up to a pH between 5.0 and 6.0. Al precipitates at pH values greater than 6.0 and causes Al toxicity which alters soil properties and root growth (Kunhikrishnan et al. 2016).

The tropical soils vary with regard to different types of ion exchange complexes. In many soils, Al and Fe oxides and some clay are responsible for anion absorption that influences the direct impact of sulfate loading and associated problems like phosphorus immobilization. Both phosphate and sulfate compete for anion absorption sites in tropical clay soils (Johnston and Chrysochoou 2016). Acidification of soils can lead to increased weathering rates of minerals, leaching of bases, and solubilization of trace metals. Soils having lower cation exchange capacity (Sanhueza et al. 1988) and low exchangeable Ca are often considered sensitive to acidification. Further increases in Al saturation and concentration in the soil solution are the major consequences of acidification.

Two types of soils most likely to be sensitive due to deposition of acidic or acidifying substances from the atmosphere are soils that are already acidic in nature and in which Al could be mobilized by additional anion leaching and soils having a substantial reduction in base saturation (Kunhikrishnan et al. 2016). The rapid deforestation in the tropics is also an important acidifying mechanism. Emissions of gases by burning of biomass, export of bases with biomass harvest, and increased leaching of acid-neutralizing cations are important factors in enhancing the soil acidification (Crutzen and Andreae 2016).

7.5.3 Effects on Litterfall and Decomposition

Studies related to the effect of air pollution on litterfall and decomposition in the tropical forests, in grasslands, and in vegetation growing in urban and other remote areas are limited. Decomposition is affected both by deposition of N and nutrients by air pollution, which alter soil properties, and by changing the foliar chemistry of trees. Emissions from industries and traffic alter the natural biogeochemical cycles, decomposition, nutrient balance, and soil fertility. Ferreira et al. (2017) found the influence of air pollution on the rate of litterfall decomposition in Guarapiranga forest in São Paulo, Brazil, and attributed these variations due to the proximity of air-polluting sources like vehicular and industrial activities around the forest site altering the dynamics of decomposition. Influence of air pollution from the urban area of São Paulo, Brazil, on litterfall stock and decomposition in the forest has been reported by Ferreira et al. (2017). It was observed that heavy metals (HMs) transported from the urban areas are the major causes of such changes apart from other factors. Singh et al. (2004) found a negative association between litter decomposition and air pollution around an industrial area in a dry tropical region of India; however, the turnover time of nutrients in the decomposing litter was higher at the site receiving maximum atmospheric depositions. Among the air pollutants, SO_2 showed significant negative correlation with mean annual litterfall. All the evidence clearly indicated that higher atmospheric depositions and gaseous and particulate pollutants significantly influence decomposition rates and nutrient cycling.

Powers and Salute (2011) compared the effect of the addition of nutrients on the decomposition of two leaf litter types from tropical dry forest trees (*Quercus oleoides* and *Gliricidia sepium*). The outcome of the experiment varied with the type of nutrient and species. The decomposition rate was enhanced with the addition of P and Zn, whereas Mg and N delayed the process while K and Ni showed no significant role in litter decomposition (Table 7.4).

7.5.4 Plant Biodiversity

Changes in species richness, dominance, evenness, density, and abundance are the first markers of a shift in biodiversity. To assess the impact of air pollution on lichen diversity, Shukla and Upreti (2011) explored lichen biodiversity in the city of Pauri and Srinagar in Garhwal Himalayas, Uttarakhand, and found a decline in lichen diversity at sites with higher pollution load. The dominance of physcoid lichens (pollution-tolerant) compared to parmeliod lichens (less pollution-tolerant) at polluted sites indicated a strong effect of air pollution on lichen diversity. The decrease in population of fruticose lichens which only accounted for 6% of the total diversity from all the studied sites was implicated with the deteriorating air quality in the study area. Reductions in the number of phorophytes (any plant on which an epiphyte grows) and anthropogenic factors (higher NOx and HMs by vehicles) were identified as the main causes behind the observed pattern at the urban site, which also showed the dominance of nitrophilous lichen (Shukla and Upreti 2011).

In seven cities of the subtropical region of Brazil, Koch et al. (2016) observed a significant effect of air pollution on lichen community composition and vitality. Fine PM was identified as a major air pollutant, which negatively influenced lichen community with NOx, Cu, and Mn. Apart from air pollutants, land uses and higher population density were also identified as major factors affecting lichen diversity as increases in surrounding urban areas were negatively correlated with lichen vitality (Table 7.4). Among the different traits used for assessment of disturbance in environmental gradient on lichen diversity, photobiont vitality (percentage of photobiont cells) was found to be more sensitive trait compared to species richness or cover (Koch et al. 2016).

Singh et al. (1994) conducted a field study around two coal-fired thermal power plants (TPP) to analyze the impact of emissions on the structure of herbaceous

Table 7.4 Summary of studies related to air pollution and plant responses

Location	Study site	Plant	Parameter	Outcome	References
Aligarh, India	Thermal power plant	*R. tuberosa*	Photosynthesis and stomatal conductance	Reduction in photosynthetic and stomatal conductance at higher pollution load	Nighat et al. (2000)
Aligarh, India	Thermal power plant	*R. tuberosa*	Stomatal characteristics	Reduction in length and width of stomata, length of the stomatal pore, stomatal density	Nighat et al. (2000)
Birbhum district, India	Forest	*S. robusta*	Transpiration index	Negative association between dust fall and transpiration index	Saha and Padhy (2012)
Hyderabad, India	Chamber experiment	*F. infectoria* *P. pinnata*	RuBP carboxylase activity and net photosynthesis	Negative association between O_3 exposure and RuBP carboxylase activity and net photosynthesis	Chapla and Kamalakar (2004)
Lucknow City, India	Urban	*C. procera*	Foliar sulfate accumulation	*C. procera* as a sulfate accumulator plant	Singh et al. (1995)
Lucknow, India	Urban	*T. nerifolia*	Stomatal size stomatal frequency	Reduction in stomatal size and increase in stomatal frequency at higher pollution load	Verma and Singh (2006)
Lucknow, India	Urban	*T. nerifolia*	Leaf area	Reduction in leaf area around traffic emission	Verma and Singh (2006)
Nagpur, India	Urban	*A. indica*	Ascorbic acid	Positive association between ascorbic acid content and pollution load	Ninave et al. (2001)
Pauri City, India	Urban	*P. hispidula*	Metal accumulation	Higher bioaccumulation of Fe, Cr, Cu, Zn, Ni, and Pb	Shukla and Upreti (2007)
Sambalpur, India	Highway	*I. carnea*	Dust accumulation and tree characteristics	The roughness of leaf surface, the small size of petiole, and smaller height of plants favor dust accumulation	Prusty et al. (2005)
Varanasi, India	Urban	*P. longifolia* *P. guajava* *M. indica* *F. benghalensis*	Carotenoids Ascorbic acid LDMC	Positive association between carotenoids Ascorbic acid LDMC with increasing pollution load	Mukherjee and Agrawal (2016)

(continued)

Table 7.4 (continued)

Location	Study site	Plant	Parameter	Outcome	References
Varanasi, India	Urban	13 tropical tree species	Leaf functional traits	PM and O_3 maximally influenced leaf functional traits in tree species	Mukherjee and Agrawal (2018)
Philippines	Urban	*P. indicus* *E. orientalis*	Photosynthesis and stomatal conductance	Increase in photosynthetic and stomatal conductance at higher pollution load	Baek and Woo (2010)
Sarawak, Malaysia	Forest	*D. lanceolata* *Macaranga* spp.	Foliar accumulation of 21 heavy metals	Higher metal accumulation in *D. lanceolata* compared to *Macaranga* spp.	Breulmann et al. (2002)
Cubatão City, Brazil	Atlantic rainforest	*T. pulchra*	Photosynthesis	Reduction in photosynthesis at higher pollution load	Moraes et al. (2002)
Cubatão, Brazil	Atlantic rainforest	*T. pulchra*	Carbon assimilation	Negative association between carbon assimilation and pollution load	Moraes et al. (2002)
Cubatão City, Brazil	Atlantic rainforest	*T. pulchra*	Chlorophyll a, Chl a/b ratio, and foliar F, N, and S concentrations	Positive association between chlorophyll a, Chl a/b ratio, and foliar F, N, and S concentrations with pollution load	Moraes et al. (2002)
Cubatão, Brazil	Atlantic forest	*T. pulchra*	Growth parameters (height, diameter, leaf and root biomass, leaf area, and whole plant biomass)	Reduction in all growth parameters at higher pollution load	Moraes et al. (2003)
Manaus, Brazil	Rainforest	10 species	PAHs in leaves, bark, twigs, stem, and wood	PAHs accumulation leave > bark > twigs > stem > wood	Krauss et al. (2005)
Port Harcourt, Nigeria	Urban	*A. cordifolia*, *M. paradisiaca*, *M. esculenta*	Stem, leaf, and petiole anatomy	Increase in number of vascular bundles at higher pollution load	Ajuru and Friday (2014)

communities. The importance value index (IVI) estimates indicated the dominance of a few plant species like *Cassia tora*, *Cynodon dactylon*, and *Dichanthium annulatum* at the sites receiving higher pollution load. On the other hand, *Paspalidium flavidum*, *Phyllanthus simplex*, and *Rungia repens* were more dominant at less polluted sites. However, some plant species like *Alysicarpus monilifer*, *Convolvulus pluricaulis*, and *Desmodium triflorum* were more or less uniformly distributed. Singh et al. (1994) also recorded significant negative correlation between SO_2 concentrations in air and species diversity of herbaceous communities in the dry tropical environment. According to Narayan et al. (1994), the successful survival of a species in the polluted area may be due to adequate biomass formation and their suitable structure, the ability to survive the lasting impact of pollutants, and the ability to reproduce under the pollution stress. Thus, the species having higher IVI values at the heavily polluted sites showed tolerance to the existing pollution load and were classified as "resistant species." Pandey et al. (2014) reported *Achyranthes aspera*, *Convolvulus alsinoides*, *D. annulatum*, *Eclipta alba*, and *Solanum nigrum* as sensitive species under the pollution stress due to coal mining activities. Species such as *Eragrostis cynosuroides* and *Setaria glauca* were identified as polluphilic species as these were only present at the polluted sites.

Pandey et al. (2014) reported changes in IVI values for sensitive and tolerant species due to air pollution around Jharia and Raniganj coalfields in India. Authors also recorded reductions in species richness of both herbaceous and woody species with increasing pollution load. Pandey et al. (2014) also observed the negative effect of SO_2 on woody vegetation around coal mine areas in Jharia and Raniganj coalfields in India. Distribution of *Ficus religiosa*, *Ficus benghalensis*, *Psidium guajava*, and *Butea monosperma* around coal mine areas was directly related to atmospheric air pollutants such as TSP, SO_2, and NO_2. Based on plant density around coal mining areas, Pandey et al. (2014) identified *F. religiosa*, *F. benghalensis*, *P. guajava*, *B. monosperma*, *Corymbia citriodora*, *M. indica*, and *Terminalia arjuna* as the most resistant species. Narayan et al. (1994) assessed the vegetation characteristics downwind of an aluminum factory in Renukoot, India, and found that long-term emissions of fluoride, SO_2, and PM have altered soil characteristics, which significantly impacted the local vegetation. Woody vegetation around the area was more influenced compared to herbaceous vegetation. *E. alba*, *C. tora*, *S. nigrum*, and *Bothriochloa pertusa* were identified as the most sensitive species, whereas *Zornia diphylla*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium*, *S. glauca*, and *Eragrostis tenella* were only recorded at the most polluted sites around the factory (Narayan et al. 1994).

Zvereva et al. (2008) found differences between effects of air pollution on plant species richness among the four terrestrial biomes (boreal and temperate forests, deserts, and tropical savanna). Lack of data from the tropical region is a major limitation to compare differences between the effects of air pollution on biodiversity from different regions of the world (Zvereva et al. 2008). Studies related to effects of N deposition on biodiversity in the tropical and subtropical regions having several biodiversity hotspots are yet to be investigated.

7.6 Air Pollution Impacts on Plant Performance

7.6.1 Growth and Morphology

Both biotic and abiotic stress tolerance in plants depend upon the ability of the plant species to regulate between growth and defense response. Higher allocation of energy in defense response may lead to lower growth, which results in changes in morphological characteristics. In saplings of *Tibouchina pulchra*, one of the most common tree species in the tropical Atlantic forest, reductions in growth parameters such as height, diameter, leaf and root biomass, leaf area, and whole plant biomass were recorded at the sites with higher air pollution load in Cubatão, Brazil (Moraes et al. 2003). Reductions in plant height, basal diameter, canopy area, root-shoot ratio, and plant biomass were also recorded by Pandey and Agrawal (1994) in a tropical urban environment with maximum reduction in *Delonix regia* followed by *C. fistula* and *Carissa carandas*. Ajuru and Friday (2014) studied the effects of PM on the anatomy of three tropical plants, *Alchornea cordifolia*, *Musa paradisiaca*, and *Manihot esculenta*, in Port Harcourt, Nigeria, and found significant effects of pollution load with an increase in the number of vascular bundles although no effect was observed in cortex, epidermis, and pith tissues (Table 7.4).

To avoid air pollution effects from traffic, plants employ different strategies such as reductions in leaf area, specific leaf area, leaf dry matter content, and leaf water content (Mukherjee and Agrawal 2016; Verma and Singh 2006). Verma and Singh (2006) recorded reduction in leaf area by 15–40% in *Thevetia nerifolia* and *F. religiosa* under higher automobile exhaust emission. Prusty et al. (2005) investigated the dust accumulation potential in vegetation near the national highway at Sambalpur, Orissa, India, and found higher dust accumulation in the leaves of *Ipomoea carnea*, *Tabernaemontana divaricata*, and *Pongamia pinnata* compared to *F. religiosa* and *Quisqualis indica*. The observed outcomes were correlated with the roughness of leaf surface, the small size of petiole, and the smaller height of plants favoring higher dust accumulation.

Leaf structure, geometry, leaf epidermal length, cuticle thickness, phyllotaxy of leaf, height of the plant, canopy size, nature of the tree, and leaf forms determine plant response to higher dust pollution (Nighat et al. 2000; Prusty et al. 2005). Prusty et al. (2005) found that dust accumulation was more in plants with smaller height compared to taller plants. Nighat et al. (2000) recorded reductions in leaf area, length and width of stomata, length of the stomatal pore, and stomatal density in *Ruellia tuberosa* due to thermal power plant emission in Aligarh, India, whereas stomatal index was unaffected (Table 7.4).

7.6.2 Plant Physiology

For proper growth and development, plants have to regulate their function according to variations in environmental conditions. Regulating physiological activities in accordance with environmental conditions provides a plant to maximize the resource utilization and maintain the growth process. Variations in physiological activities such as photosynthesis, stomatal conductance, respiration, transpiration, and photosynthetic efficiency are known under air pollution stress conditions (Baek and Woo 2010; Moraes et al. 2002).

Moraes et al. (2002) found a reduction in photosynthesis rate in *T. pulchra* at polluted site compared to control in Cubatão, Brazil, indicating the influence of air pollution in damaging stomata and pathways related to light and CO_2 fixation. Similarly, reductions in photosynthetic rate and stomatal conductance were observed in *R. tuberosa* plants receiving thermal power plant emission in Aligarh, India (Nighat et al. 2000). In contrast, *Pterocarpus indicus* and *Erythrina orientalis* showed enhancement in photosynthetic rate as well as stomatal conductance at sites with higher pollution load (Baek and Woo 2010). The contradictory response showed compensation ability by increasing photosynthetic rate in response to pigment degradation and high carbon utilization of the test plant at higher pollution load (Baek and Woo 2010).

Saha and Padhy (2012) compared the effects of stone dust deposition on the rate of transpiration in *Shorea robusta* plant in the polluted and non-polluted forest of Birbhum district, India. Transpiration rate was declined at polluted forest due to damage to leaf and deposition of dust particles at the stomatal surface. Higher SPM concentrations and dust fall also lowered the transpiration index (Table 7.4). Carbon assimilation declined at higher pollution load, whereas stomatal conductance remained unchanged in *T. pulchra* at Cubatão, Brazil (Moraes et al. 2002). Traffic-related pollutants in high concentrations modified plant physiology through altering the stomatal response. Verma and Singh (2006) recorded 70% decline in stomatal size, whereas stomatal frequency increased up to 50% in *T. nerifolia* at sites with higher pollution load. Alterations in foliar surface configuration were also recorded in plants exposed to traffic-related pollutants. Chapla and Kamalakar (2004) found a significant negative effect of O_3 fumigation (40–120 ppb) on RuBP carboxylase activity with percent reductions varying from 10 to 32 in *Bauhinia variegata* followed by 10–23 in *Ficus infectoria* and 9–15 in *P. pinnata*. Percent reduction in photosynthesis was maximum in *F. infectoria* (16–39) followed by *P. pinnata* (7–31) and *B. variegata* (6–26) due to O_3 fumigation.

7.6.3 Leaf Functional Traits

Leaf functional traits are most widely used in the assessment of plant response to biotic and abiotic stresses. Leaf functional traits such as leaf mass per area or specific leaf area, tissue thickness, leaf area, foliar C and N contents, photosynthetic pigments, antioxidants, and relative water content vary in relation to the environmental conditions (Table 7.4). Therefore, these characteristics provide the opportunity to correlate the variations in relation to changing environment under natural as well as in modified systems. The increases in antioxidants and defense-related metabolites are the primary response of plants against air pollution stress. Verma and Singh (2006) recorded increases in foliar cysteine content at higher traffic pollution load with maximum percent increases of 44% and 30%, respectively, in *F. religiosa* and *T. nerifolia*. Ninave et al. (2001) also observed an increase in ascorbic acid content in plants at the polluted environment.

Verma and Singh (2006) recorded reductions in Chl a, Chl b, and carotenoid contents by 6–64% at higher pollution load in both *T. nerifolia* and *F. religiosa* in Lucknow, India, indicating a decrease in productivity at a higher load of air pollutants. A similar trend was also observed for foliar protein content in both plants indicating inhibition in protein synthesis or damage to existing protein although percent reduction in protein content was lower than the photosynthetic pigments indicating more sensitivity of pigments to air pollutants (Verma and Singh 2006). In contrast, Ninave et al. (2001) found an increase in Chl content in all the studied plants except for *Polyalthia longifolia* at polluted environments. Based on responses of plants, *Azadirachta indica* was identified as tolerant species in the urban environment of Nagpur, India. Due to foliar dust deposition, declines in both chlorophyll and carotenoid contents were observed in most of the plants. Chl a as well as total chlorophyll showed maximum reductions of 46.5% and 45.4% in *F. benghalensis* due to dust deposition (Prusty et al. 2005). Dust contains many organic and inorganic compounds which on entry into plant tissues cause increases in reactive oxygen species (ROS) and primarily damage to the membrane and pigments. Moraes et al. (2003) found a decline in ascorbate concentration in *T. pulchra* while increases in chlorophyll a, Chl a/b ratio, and foliar F, N, and S concentrations at polluted site compared to control in Cubatão, Brazil. The increase in pigment concentration is attributed to increasing leaf N content, indicating the utilization of atmospheric NOx and NH_4^+ in N assimilation. Pandey and Agrawal (1994), however, recorded reductions in chlorophyll, ascorbic acid, and nitrogen contents in leaves, whereas sulfate content showed increment with increasing pollution load in three tropical tree species. Baek and Woo (2010) assessed the responses of *P. indicus* and *E. orientalis* growing in four sites within the Philippines with differential pollution load. In both the test plants, chlorophyll content and Chl a/b ratio declined at sites with higher pollution load, whereas antioxidative enzymes showed increments. A decrease in the size of starch grains in plant leaves indicated consumption of stored carbon at the expense of defense response (Baek and Woo 2010).

Moraes et al. (2002) found higher variations in water-soluble thiols and peroxidase activity at higher pollution load compared to ascorbic acid in *P. guajava* and *P. cattleyanum* around the industrial complex of Cubatão, SE Brazil. Mukherjee and Agrawal (2016) also observed an increase in ascorbic acid content in four tropical tree species (*M. indica*, *P. longifolia*, *F. benghalensis*, and *P. guajava*) growing at higher pollution load at different parks in Varanasi City, India. Baek and Woo (2010) observed an increase in thickness of cell wall in response to pollution load in *P. indicus*, which may be due to increase in defense-related metabolites to protect membrane damage (Fig. 7.4).

In the urban area of Varanasi City, Mukherjee and Agrawal (2016) found an increase in photosynthetic pigments with an increase in air pollution load in *M. indica* and *P. longifolia*, whereas *F. benghalensis* and *P. guajava* showed marked reductions. Carotene content showed a significant increase with higher pollution

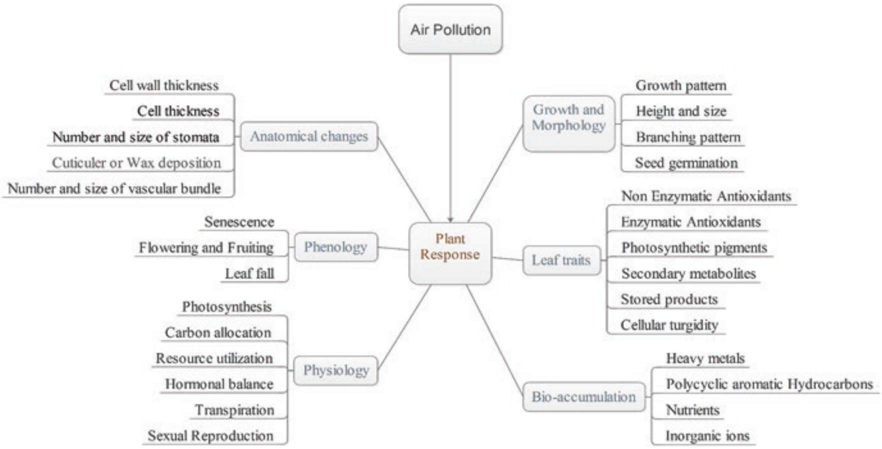

Fig. 7.4 Different responses of plants in relation to air pollution tolerance

load in all the studied plant species with a maximum increase of 88% in *P. longifolia*. Chl a/b ratio as well as TChl/Car ratio showed reductions in most plants with increasing pollution load. Leaf area, leaf dry matter content (LDMC), relative water content (RWC), and specific leaf area (SLA) were suggested to be important markers for stress tolerance under air pollution stress (Mukherjee and Agrawal 2016; Pandey and Agrawal 1994). Most studies have identified increases or maintenance of leaf biomass allocation and cellular turgidity at higher pollution load in tolerant plant species (Fig. 7.4) (Mukherjee and Agrawal 2016).

7.6.4 Foliar Bioaccumulation

Plants have the ability to accumulate, detoxify, and concentrate pollutants (De França et al. 2004; Mukherjee et al. 2016) that enable them to tolerate harsh environments. PM constituents like HMs, PAHs, and ions after deposition can directly enter the leaf through stomata or via absorption through root after getting deposited in the soil. Nakazato et al. (2016) assessed foliar accumulation and enrichment factor for 36 elements in *P. guajava* and *T. pulchra* trees of the Atlantic rainforest and found *P. guajava* as a better accumulator of metals with distinct spatial-temporal variations with pollution load. Authors have also suggested the use of *P. guajava* for biomonitoring of toxic elements. De França et al. (2004) assessed the foliar metal accumulation in native trees of the tropical Atlantic forest located at the southwest portion of São Paulo State, Brazil, and found the lowest bioaccumulation of metals in *Euterpe edulis*, with exception of Cs and Zn, whereas the highest concentration of Se was found in the leaves of *Tetrastylidium grandifolium* and *Eugenia cuprea*. *Hyeronima alchorneoides* tree was identified as potential Co hyperaccumulator compared to other trees with 80–300 times higher accumulation of Co (Table 7.4).

Moraes et al. (2002) reported higher bioaccumulation of F, S, and N in *P. guajava* compared to *P. cattleyanum* and *M. indica* around the industrial complex of Cubatão, Brazil (Moraes et al. 2002). Authors also found 2–2.6 times higher accumulation of F in *P. guajava* compared to other plants. Breulmann et al. (2002) analyzed 21 chemical elements in emergent (*Dryobalanops lanceolata*) and pioneer species (*Macaranga* spp.) in a tropical forest in Sarawak, Malaysia. Higher bioaccumulation was recorded in pioneer species compared to emergent species, which may be due to higher physiological activities in the former species. Higher bioaccumulation was also found due to extensive forest fire raging in Borneo and other parts of Southeast Asia, which increased the atmospheric load of certain elements. Singh et al. (1995) identified *Calotropis procera* as the best accumulator plant for Pb and sulfate around roadside receiving auto exhaust pollution in Lucknow City, India. *C. procera* followed by *T. nerifolia*, *D. sissoo*, and *Eucalyptus* sp. showed significant positive correlation between sulfate in leaves and SO_2 in the ambient air, whereas correlations were insignificant for *P. longifolia* and *P. glabra*. Agrawal and Singh (2000) recorded increases in total S content by 41%, 25%, 35%, 27%, 33%, and 24%, respectively, in *M. indica*, *P. guajava*, *C. siamea*, *D. regia*, *Eucalyptus hybrid*, and *Bougainvillea spectabilis* around two thermal power plants in the Sonbhadra district of Uttar Pradesh, India, and found direct correlation with average SO_2 concentrations in the ambient air. Plants growing near the power plants also showed higher bioaccumulation of Ca, K, Mn, Fe, Cd, Pb, and Ni, whereas the total N content was reduced.

High metal bioaccumulation was also reported in lichens (Shukla and Upreti 2007). At five different sites of Pauri City in Garhwal Himalaya, India, metal accumulation in *Phaeophyscia hispidula*, a common foliose lichen, was found higher for Fe, Cr, Cu, Zn, Ni, and Pb, which correlated well with traffic load at different sites. PAHs in leaves, bark, twigs, stem, and wood were estimated in a tropical rainforest near Manaus, Brazil, by Krauss et al. (2005). The order of PAHs accumulation was maximum in leaves followed by bark, twigs, stem, and wood. The study also identified that atmosphere is the major source of PAHs accumulation in plants.

Most of the studies analyzed in this review article showed a negative effect of air pollutants on growth and morphology with reductions in leaf area, height, biomass, size of stomata, and overall canopy size. Physiological parameters also showed a significant negative effect of air pollutants with variable responses in different plant species. Most of the tolerant species showed increases in enzymatic and nonenzymatic antioxidants with an increase in pollution load to cope up with the oxidative stress. The sensitive species, however, showed marked reductions in most of the studied leaf functional traits. Significant variability in bioaccumulation pattern among different plant groups and species was also ascertained. Higher accumulation in most of the plant species under highly polluted environment indicates their tolerance which depends upon the nature of the plant, leaf characteristics, biochemistry, and physiology.

7.7 Conclusions

The tropical and subtropical regions harbor highly diverse ecosystems of the world. Overexploitation of resources and increasing demands for natural resources have drastically altered the dynamics of the tropical ecosystems. Air pollution is one of the major root causes of such changes in the tropics. Air pollution in the form of particulate matter, O_3, nitrogen deposition, and hydrocarbons has deteriorated the air quality in the tropics. Both coarse and fine PM are identified as major air pollutants in Southeast Asia, in South America, and in West and East Africa. NO_2 and O_3 are the major gaseous air pollutants in the tropics, whereas SO_2 concentrations are significantly lowered down in recent time. In most of the tropical region, air pollutants are identified as a major stress factor for vegetation. The effects are more significant in urban areas where air pollutant sources such as industrial, traffic, and combustion activities are higher. Apart from anthropogenic emissions, forest fires and prevailing meteorological conditions in the tropics also contribute to air pollution load. Air pollutants influence plants diversity by altering soil quality, litterfall, and decomposition rate. Vegetation responds to air pollution load by modifying the growth and morphological pattern, physiological activities, varying leaf functional traits, and bioaccumulation of pollutants. Lack of air pollution response studies in the tropical regions and different vegetation types limited the scope of this chapter to identify a broad range of air pollution effects in the tropics, although current evidence clearly highlights the negative influence of air pollution in different tropical and subtropical regions of the world. To estimate future effects of air pollution in the tropics, it is necessary to estimate projections of future emission patterns, air quality, deposition pattern, biodiversity, and pollution response assessment in the tropics.

Acknowledgments Authors are thankful to Head, Department of Botany, and Coordinator, DST-FIST and CAS in Botany, Banaras Hindu University, for providing the necessary computer and library facilities. Department of Science and Technology (DST), India, is acknowledged for providing financial support in the form of an Inspire fellowship (IF120768) to Arideep Mukherjee, and Asian-Pacific Network for Global Change Research (M-21-164) is acknowledged for providing financial support as RA to Dr. Bhanu Pandey. Authors are also thankful to the anonymous reviewer and editor for their valuable suggestions in improving the quality of the manuscript.

References

Agrawal M, Agrawal SB (1999) Effects of air pollution on plant diversity. In: Agrawal SB, Agrawal M (eds) Environmental pollution and plant responses. CRC/Lewis Publishers, New York, pp 154–176

Agrawal M, Singh J (2000) Impact of coal power plant emission on the foliar elemental concentrations in plants in a low rainfall tropical region. Environ Monit Assess 60:261–282. https://doi.org/10.1023/A:1006135317896

Agrawal M, Nandi PK, Rao DN (1983) Ozone and sulphur dioxide effects on Panicum miliaceum plants. Bull Torrey Bot Club 110:435–441

Ajuru MG, Friday U (2014) Effects of particulate matter on the anatomy of some tropical plants (Alchonea cordifolia, Musa paradisiaca, and Manihot esculenta). Int J Sci Technol Res 3:304–308

Alejo D, Morales MC, De La Torre JB et al (2013) Seasonal trends of atmospheric nitrogen dioxide and sulfur dioxide over North Santa Clara, Cuba. Environ Monit Assess 185:6023–6033. https://doi.org/10.1007/s10661-012-3003-4

Awang NR, Elbayoumi M, Ramli NA, Yahaya AS (2016) Diurnal variations of ground-level ozone in three port cities in Malaysia. Air Qual Atmos Health 9:25–39. https://doi.org/10.1007/s11869-015-0334-7

Ayi Fanou L, Mobio TA, Creppy EE et al (2006) Survey of air pollution in Cotonou, Benin – Air monitoring and biomarkers. Sci Total Environ 358:85–96. https://doi.org/10.1016/j.scitotenv.2005.03.025

Azmi SZ, Latif MT, Ismail AS et al (2010) Trend and status of air quality at three different monitoring stations in the Klang Valley, Malaysia. Air Qual Atmos Health 3:53–64. https://doi.org/10.1007/s11869-009-0051-1

Badarinath KVS, Kharol SK, Reddy RR et al (2009) Black carbon aerosol mass concentration variation in urban and rural environments of India—a case study. Atmos Sci Lett 10:29–33. https://doi.org/10.1002/asl.206

Baek SG, Woo SY (2010) Physiological and biochemical responses of two tree species in urban areas to different air pollution levels. Photosynthetica 48:23–29. https://doi.org/10.1007/s11099-010-0005-8

Baumbach G, Vogt U, Hein KRG et al (1995) Air pollution in a large tropical city with a high traffic density—results of measurements in Lagos, Nigeria. Sci Total Environ 169:25–31. https://doi.org/10.1016/0048-9697(95)04629-F

Baxla SP, Roy AA, Gupta T et al (2009) Analysis of diurnal and seasonal variation of submicron outdoor aerosol mass and size distribution in a Northern Indian city and its correlation to black carbon. Aerosol Air Qual Res 9:458–469. https://doi.org/10.4209/aaqr.2009.03.0017

Begum BA, Hossain A, Nahar N et al (2012) Organic and black carbon in PM2.5 at an urban site at Dhaka, Bangladesh. Aerosol Air Qual Res 12:1062–1072. https://doi.org/10.4209/aaqr.2012.05.0138

Beig G, Singh V (2007) Trends in tropical tropospheric column ozone from satellite data and MOZART model. Geophys Res Lett 34:1–5. https://doi.org/10.1029/2007GL030460

Breulmann G, Markert B, Weckert V et al (2002) Heavy metals in emergent trees and pioneers from tropical forest with special reference to forest fires and local pollution sources in Sarawak, Malaysia. Sci Total Environ 285:107–115. https://doi.org/10.1016/S0048-9697(01)00899-3

Cavalcante RM, Rocha CA, De Santiago ÍS et al (2017) Influence of urbanization on air quality based on the occurrence of particle-associated polycyclic aromatic hydrocarbons in a tropical semiarid area (Fortaleza-CE, Brazil). Air Qual Atmos Health 10:437–445. https://doi.org/10.1007/s11869-016-0434-z

Chapla J, Kamalakar JA (2004) Metabolic responses of tropical trees to ozone pollution. J Environ Biol 25(3):287–290

Chaudhary N, Agrawal SB (2014) Role of gamma radiation in changing phytotoxic effect of elevated level of ozone in Trifolium alexandrinum L. (Clover). Atmos Pollut Res 5:104–112. https://doi.org/10.5094/APR.2014.013

Cho K, Tiwari S, Agrawal SB et al (2011) Tropospheric ozone and plants: absorption, responses, and consequences. In: Whitacre DM (ed) Reviews of environmental contamination and toxicology, vol 212. Springer New York, New York, pp 61–111

Cooper OR, Parrish DD, Ziemke J et al (2014) Global distribution and trends of tropospheric ozone: an observation-based review. Elem Sci Anthr 2:29. https://doi.org/10.12952/journal.elementa.000029

CPCB (2009). Central Pollution Control Board. National ambient air quality standards. http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php. Accessed 1 May 2017

Crang RE, McQuattie CJ (1986) Qualitative and quantitative effects of acid misting and two air pollutants on foliar structures of Liriodendron tulipifera. Can J Bot 64:1237–1243. https://doi.org/10.1139/b86-170

Crutzen PJ, Andreae MO (2016) Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. In: Crutzen PJ, Brauch HG (eds) Paul J. Crutzen: a pioneer on atmospheric chemistry and climate change in the anthropocene. Springer, Cham, pp 165–188

Crutzen PJ, Giedel LT (1983) A two-dimensional photochemical model of the atmosphere. 2: the tropospheric budgets of anthropogenic chlorocarbons {CO}, {CH_4}, {CH_3Cl} and the effect of various {NO_x} sources on tropospheric ozone. J Geophys Res 88:6641–6661. https://doi.org/10.1029/JC088iC11p06641

Dallarosa JB, Mônego JG, Teixeira EC et al (2005) Polycyclic aromatic hydrocarbons in atmospheric particles in the metropolitan area of Porto Alegre, Brazil. Atmos Environ 39:1609–1625. https://doi.org/10.1016/j.atmosenv.2004.10.045

De França EJ, De Nadai Fernades EA, Bacchi MA, Saiki M (2004) Native trees as biomonitors of chemical elements in the biodiversity conservation of the Atlantic Forest. J Atmos Chem 49:579–592. https://doi.org/10.1007/s10874-004-1267-y

Dey S, Di Girolamo L, van Donkelaar A et al (2012) Variability of outdoor fine particulate (PM2.5) concentration in the Indian Subcontinent: a remote sensing approach. Remote Sens Environ 127:153–161. https://doi.org/10.1016/j.rse.2012.08.021

Dionisio KL, Arku RE, Hughes AF et al (2010) Air pollution in Accra neighborhoods: spatial, socioeconomic, and temporal patterns. Environ Sci Technol 44:2270–2276. https://doi.org/10.1021/es903276s

Doumbia EHT, Liousse C, Galy-Lacaux C et al (2012) Real time black carbon measurements in West and Central Africa urban sites. Atmos Environ 54:529–537. https://doi.org/10.1016/j.atmosenv.2012.02.005

Ferreira ML, Portella Ribeiro A, Rodrigues Albuquerque C et al (2017) Air contaminants and litter fall decomposition in urban forest areas: the case of São Paulo – SP, Brazil. Environ Res 155:314–320. https://doi.org/10.1016/j.envres.2017.02.023

Gupta GP, Kumar B, Kulshrestha UC (2016) Impact and pollution indices of urban dust on selected plant species for green belt development: mitigation of the air pollution in NCR Delhi, India. Arab J Geosci 9:1–15. https://doi.org/10.1007/s12517-015-2226-4

Gurjar BR, Ravindra K, Nagpure AS (2016) Air pollution trends over Indian megacities and their local-to-global implications. Atmos Environ 142:475–495. https://doi.org/10.1016/j.atmosenv.2016.06.030

Guttikunda SK, Goel R, Mohan D et al (2015) Particulate and gaseous emissions in two coastal cities—Chennai and Visakhapatnam, India. Air Qual Atmos Health 8:559–572. https://doi.org/10.1007/s11869-014-0303-6

Hayasaka H, Noguchi I, Putra EI et al (2014) Peat-fire-related air pollution in Central Kalimantan, Indonesia. Environ Pollut 195:257–266. https://doi.org/10.1016/j.envpol.2014.06.031

Heil A, Langmann B, Aldrian E (2007) Indonesian peat and vegetation fire emissions: study on factors influencing large-scale smoke haze pollution using a regional atmospheric chemistry model. Mitig Adapt Strateg Glob Chang 12:113–133. https://doi.org/10.1007/s11027-006-9045-6

Herawati H, Santoso H (2011) Tropical forest susceptibility to and risk of fire under changing climate: a review of fire nature, policy and institutions in Indonesia. For Policy Econ 13:227–233. https://doi.org/10.1016/j.forpol.2011.02.006

Heue KP, Coldewey-Egbers M, Delcloo A et al (2016) Trends of tropical tropospheric ozone from 20 years of European satellite measurements and perspectives for the Sentinel-5 Precursor. Atmos Meas Tech 9:5037–5051. https://doi.org/10.5194/amt-9-5037-2016

Hung NTQ, Lee SB, Hang NT et al (2014) Characterization of black carbon at roadside sites and along vehicle roadways in the Bangkok Metropolitan Region. Atmos Environ 92:231–239. https://doi.org/10.1016/j.atmosenv.2014.04.011

Johnston CP, Chrysochoou M (2016) Mechanisms of chromate, selenate, and sulfate adsorption on al-substituted ferrihydrite: implications for ferrihydrite surface structure and reactivity. Environ Sci Technol 50:3589–3596. https://doi.org/10.1021/acs.est.5b05529

Kaur S, Senthilkumar K, Verma VK et al (2013) Preliminary analysis of polycyclic aromatic hydrocarbons in air particles (PM10) in Amritsar, India: sources, apportionment, and possible risk implications to humans. Arch Environ Contam Toxicol 65:382–395. https://doi.org/10.1007/s00244-013-9912-6

Klumpp A, Domingos M, Klumpp G (1996) Assessment of the vegetation risk by fluoride emissions from fertiliser industries at Cubatão. Brazil Sci Total Environ 192:219–228. https://doi.org/10.1016/S0048-9697(96)05298-9

Koch NM, Branquinho C, Matos P et al (2016) The application of lichens as ecological surrogates of air pollution in the subtropics: a case study in South Brazil. Environ Sci Pollut Res 23:20819–20834. https://doi.org/10.1007/s11356-016-7256-2

Krauss M, Wilcke W, Martius C et al (2005) Atmospheric versus biological sources of polycyclic aromatic hydrocarbons (PAHs) in a tropical rain forest environment. Environ Pollut 135:143–154. https://doi.org/10.1016/j.envpol.2004.09.012

Kumar R, Gupta A, Kumari K, Srivastava S (2004) Simultaneous measurements of SO2, NO2, HNO3 and NH3: seasonal and spatial variations. Curr Sci 87:1108–1115

Kumar A, Singh D, Singh BP et al (2015) Spatial and temporal variability of surface ozone and nitrogen oxides in urban and rural ambient air of Delhi-NCR, India. Air Qual Atmos Health 8:391–399. https://doi.org/10.1007/s11869-014-0309-0

Kunhikrishnan A, Thangarajan R, Bolan NS et al (2016) Functional relationships of soil acidification, liming, and greenhouse gas flux. Adv Agron 139:1–71. https://doi.org/10.1016/bs.agron.2016.05.001

Laurance WF, Carolina Useche D, Rendeiro J et al (2012) Averting biodiversity collapse in tropical forest protected areas. Nature 489:290–294

Le TH, Nguyen TNT, Lasko K et al (2014) Vegetation fires and air pollution in Vietnam. Environ Pollut 195:267–275. https://doi.org/10.1016/j.envpol.2014.07.023

Mallik C, Lal S (2014) Seasonal characteristics of SO2, NO2, and CO emissions in and around the Indo-Gangetic Plain. Environ Monit Assess 186:1295–1310. https://doi.org/10.1007/s10661-013-3458-y

Marinoni A, Cristofanelli P, Laj P et al (2010) Aerosol mass and black carbon concentrations, a two year record at NCO-P (5079 m, Southern Himalayas). Atmos Chem Phys 10:8551–8562. https://doi.org/10.5194/acp-10-8551-2010

Masih J, Singhvi R, Kumar K et al (2012) Seasonal variation and sources of polycyclic aromatic hydrocarbons (PAHs) in indoor and outdoor air in a semi arid tract of Northern India. Aerosol Air Qual Res 12:515–525. https://doi.org/10.4209/aaqr.2011.11.0192

Mmari AG, Potgieter-Vermaak SS, Bencs L et al (2013) Elemental and ionic components of atmospheric aerosols and associated gaseous pollutants in and near Dar es Salaam, Tanzania. Atmos Environ 77:51–61. https://doi.org/10.1016/j.atmosenv.2013.04.061

Moraes RM, Klumpp A, Furlan CM et al (2002) Tropical fruit trees as bioindicators of industrial air pollution in southeast Brazil. Environ Int 28:367–374. https://doi.org/10.1016/S0160-4120(02)00060-0

Moraes RM, Delitti WBC, Moraes JAPV (2003) Gas exchange, growth, and chemical parameters in a native Atlantic forest tree species in polluted areas of Cubatão, Brazil. Ecotoxicol Environ Saf 54:339–345. https://doi.org/10.1016/S0147-6513(02)00067-2

Moreira-Nordemann LM, Forti MC, Lascio VALD et al (1988) Acidification in Southeastern Brazil. In: Henning R, Herrera R (eds) Acidification in tropical countries. Wiley, New York, pp 257–296

Mudd JB (ed) (2012) Responses of plants to air pollution. Elsevier

Mukherjee A, Agrawal M (2016) Pollution response score of tree species in relation to ambient air quality in an urban area. Bull Environ Contam Toxicol 96:1–6. https://doi.org/10.1007/s00128-015-1679-1

Mukherjee A, Agrawal M (2017a) A global perspective of fine particulate matter pollution and its health effects. In: Gunther F.A., de Voogt P. (eds) Reviews of environmental contamination and toxicology (continuation of residue reviews), 244:5–51 Springer, Cham.

Mukherjee A, Agrawal M (2017b) World air particulate matter: sources, distribution and health effects. Environ Chem Lett 15:283–309. https://doi.org/10.1007/s10311-017-0611-9

Mukherjee A, Agrawal M (2018) Use of GLM approach to assess the responses of tropical trees to urban air pollution in relation to leaf functional traits and tree characteristics. Ecotoxicol Environ Saf 152:42–54. https://doi.org/10.1016/j.ecoenv.2018.01.038

Mukherjee A, Agrawal SB, Agrawal M (2016) Heavy metal accumulation potential and tolerance in tree and grass species. In: Singh A, Prasad SM, Singh RP (eds) Plant responses to Xenobiotics. Springer Singapore, Singapore, pp 177–210

Nakazato RK, Rinaldi MCS, Domingos M (2016) Tropical trees: are they good alternatives for biomonitoring the atmospheric level of potential toxic elements near to the Brazilian Atlantic Rainforest? Ecotoxicol Environ Saf 134:72–79. https://doi.org/10.1016/j.ecoenv.2016.08.013

Narayan D, Agrawal M, Pandey J, Singh J (1994) Changes in vegetation characteristics downwind of an aluminium factory in India. Ann Bot 73:557–565. https://doi.org/10.1006/anbo.1994.1069

Nighat F, Mahmooduzzafar, Iqbal M (2000) Stomatal conductance, photosynthetic rate, and pigment content in Ruellia tuberosa leaves as affected by coal-smoke pollution. Biol Plant 43:263–267. https://doi.org/10.1023/A:1002712528893

Ninave SY, Chaudhari PR, Gajghate DG, Tarar JL (2001) Foliar biochemical features of plants as indicators of air pollution. Bull Environ Contam Toxicol 67:133–140. https://doi.org/10.1007/s001280101

Nishanth T, Satheesh Kumar MK, Valsaraj KT (2012) Variations in surface ozone and NOx at Kannur: a tropical, coastal site in India. J Atmos Chem 69:101–126. https://doi.org/10.1007/s10874-012-9234-5

Oka E, Tagami Y, Oohashi T, Kondo N (2004) A physiological and morphological study on the injury caused by exposure to the air pollutant, peroxyacetyl nitrate (PAN), based on the quantitative assessment of the injury. J Plant Res 117:27–36. https://doi.org/10.1007/s10265-003-0127-1

Pandey J, Agrawal M (1994) Evaluation of air pollution phytotoxicity in a seasonally dry tropical urban environment using three woody perennials. New Phytol 126:53–61. https://doi.org/10.1111/j.1469-8137.1994.tb07529.x

Pandey J, Agrawal M, Khanam N et al (1992) Air pollutant concentrations in Varanasi, India. Atmos Environ Part B Urban Atmos 26:91–98. https://doi.org/10.1016/0957-1272(92)90040-Y

Pandey B, Agrawal M, Singh S (2014) Coal mining activities change plant community structure due to air pollution and soil degradation. Ecotoxicology 23:1474–1483. https://doi.org/10.1007/s10646-014-1289-4

Panicker AS, Pandithurai G, Safai PD et al (2010) On the contribution of black carbon to the composite aerosol radiative forcing over an urban environment. Atmos Environ 44:3066–3070. https://doi.org/10.1016/j.atmosenv.2010.04.047

Pereira EG, Oliva MA, Kuki KN, Cambraia J (2009) Photosynthetic changes and oxidative stress caused by iron ore dust deposition in the tropical CAM tree Clusia hilariana. Trees - Struct Funct 23:277–285. https://doi.org/10.1007/s00468-008-0275-y

Pereira TS, Beltrami LS, Rocha JAV et al (2013) Toxicogenetic monitoring in urban cities exposed to different airborne contaminants. Ecotoxicol Environ Saf 90:174–182. https://doi.org/10.1016/j.ecoenv.2012.12.029

Powers JS, Salute S (2011) Macro- and micronutrient effects on decomposition of leaf litter from two tropical tree species: inferences from a short-term laboratory incubation. Plant Soil 346:245–257. https://doi.org/10.1007/s11104-011-0815-x

Pozo K, Harner T, Rudolph A et al (2012) Survey of persistent organic pollutants (POPs) and polycyclic aromatic hydrocarbons (PAHs) in the atmosphere of rural, urban and industrial areas of Concepción, Chile, using passive air samplers. Atmos Pollut Res 3:426–434. https://doi.org/10.5094/APR.2012.049

Provençal S, Kishcha P, da Silva AM et al (2017) AOD distributions and trends of major aerosol species over a selection of the world's most populated cities based on the 1st version of NASA's MERRA Aerosol Reanalysis. Urban Clim 20:168–191. https://doi.org/10.1016/j.uclim.2017.04.001

Prusty BAK, Mishra PC, Azeez PA (2005) Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. Ecotoxicol Environ Saf 60:228–235. https://doi.org/10.1016/j.ecoenv.2003.12.013

Qu Y, An J, He Y et al (2016) An overview of emissions of SO 2 and NO x and the long-range transport of oxidized sulfur and nitrogen pollutants in East Asia. J Environ Sci 44:13–25. https://doi.org/10.1016/j.jes.2015.08.028

Ramachandran S, Rajesh TA (2007) Black carbon aerosol mass concentrations over Ahmedabad, an urban location in western India: comparison with urban sites in Asia, Europe, Canada, and the United States. J Geophys Res Atmos 112:1–19. https://doi.org/10.1029/2006JD007488

Raysoni AU, Sarnat JA, Sarnat SE et al (2011) Binational school-based monitoring of traffic-related air pollutants in El Paso, Texas (USA) and Ciudad Juárez, Chihuahua (Mexico). Environ Pollut 159:2476–2486. https://doi.org/10.1016/j.envpol.2011.06.024

Reddy KK, Naja M, Ojha N et al (2012a) Influences of the boundary layer evolution on surface ozone variations at a tropical rural site in India. J Earth Syst Sci 121:911–922. https://doi.org/10.1007/s12040-012-0200-z

Reddy SKB, Raghavendra Kumar K, Balakrishnaiah G et al (2012b) Potential source regions contributing to seasonal variations of black carbon aerosols over Anantapur in southeast India. Aerosol Air Qual Res 12:340–354. https://doi.org/10.4209/aaqr.2011.10.0159

Rodrigues-Silva F, Santos U de P, Saldiva PHN et al (2012) Health risks and economic costs of absenteeism due to air pollution in São Paulo, Brazil. Aerosol Air Qual Res 12:826–833. https://doi.org/10.4209/aaqr.2011.12.0235

Romero R, Sienra R, Richter P (2002) Efficient screening method for determination of polycyclic aromatic hydrocarbons (PAHs) in airborne particles. Application in real samples of Santiago–Chile metropolitan urban area. Atmos Environ 36:2375–2381. https://doi.org/10.1016/S1352-2310(02)00161-9

Saha DC, Padhy PK (2012) Effect of particulate pollution on rate of transpiration in Shorea robusta at Lalpahari forest. Trees 26:1215–1223. https://doi.org/10.1007/s00468-012-0697-4

Sahu SK, Pandit GG, Puranik VD (2008) Dry deposition of polycyclic aromatic hydrocarbons associated with atmospheric participate matters in an urban site, Mumbai, India. Aerosol Air Qual Res 8:437–446

Salako GO, Hopke PK, Cohen DD et al (2012) Exploring the variation between EC and BC in a variety of locations. Aerosol Air Qual Res 12:1–7. https://doi.org/10.4209/aaqr.2011.09.0150

Salam A, Hossain T, Siddique MNA, Alam AMS (2008) Characteristics of atmospheric trace gases, particulate matter, and heavy metal pollution in Dhaka, Bangladesh. Air Qual Atmos Health 1:101–109. https://doi.org/10.1007/s11869-008-0017-8

Sanders GE, Robinson AD, Geissler PA, Colls JJ (1992) Yield stimulation of a commonly grown cultivar of Phaseolus vulgaris L. at near-ambient ozone concentrations. New Phytol 122:63–70. https://doi.org/10.1111/j.1469-8137.1992.tb00053.x

Sanhueza E, Cuenca G, Gomez MJ et al (1988) Characterization of the Venezuelan environment and its potential for acidification. In: Henning R, Herrera R (eds) Acidification in tropical countries. Wiley, New York, pp 197–255

Seinfeld JH, Pandis SN (2016) Atmospheric chemistry and physics: from air pollution to climate change. Wiley, Hoboken

Sharma RK, Bhattarai BK, Sapkota BK et al (2012) Black carbon aerosols variation in Kathmandu valley, Nepal. Atmos Environ 63:282–288. https://doi.org/10.1016/j.atmosenv.2012.09.023

Shaw PJA, Holland MR, Darrall NM, Mcleod AR (1993) The occurrence of SO2-related foliar symptoms on Scots pine (Pinus sylvestris L.) in an open-air forest fumigation experiment. New Phytol 123:143–152. https://doi.org/10.1111/j.1469-8137.1993.tb04540.x

Shores CA, Klapmeyer ME, Quadros ME, Marr LC (2013) Sources and transport of black carbon at the California-Mexico border. Atmos Environ 70:490–499. https://doi.org/10.1016/j.atmosenv.2012.04.031

Shukla V, Upreti DK (2007) Heavy metal accumulation in Phaeophyscia hispidula en route to Badrinath, Uttaranchal, India. Environ Monit Assess 131:365–369. https://doi.org/10.1007/s10661-006-9481-5

Shukla V, Upreti DK (2011) Changing lichen diversity in and around urban settlements of Garhwal Himalayas due to increasing anthropogenic activities. Environ Monit Assess 174:439–444. https://doi.org/10.1007/s10661-010-1468-6

Sicard P, Augustaitis A, Belyazid S et al (2016) Global topics and novel approaches in the study of air pollution, climate change and forest ecosystems. Environ Pollut 213:977–987. https://doi.org/10.1016/j.envpol.2016.01.075

Silva AA, Tomaz LM (2013) Surface ozone concentrations and local cloud cover at an urban, tropical site in the southern hemisphere. J Atmos Sol Terr Phys 105–106:54–60. https://doi.org/10.1016/j.jastp.2013.08.002

Singh RK, Agrawal M (2005) Atmospheric depositions around a heavily industrialized area in a seasonally dry tropical environment of India. Environ Pollut 138:142–152. https://doi.org/10.1016/j.envpol.2005.02.009

Singh J, Agrawal M, Narayan D (1994) Effect of power plant emissions on plant community structure. Ecotoxicology 3:110–122. https://doi.org/10.1007/BF00143409

Singh N, Yunus M, Srivastava K et al (1995) Monitoring of auto exhaust pollution by roadside plants. Environ Monit Assess 34:13–25. https://doi.org/10.1007/BF00546243

Singh RK, Dutta RK, Agrawal M (2004) Litter decomposition and nutrient release in relation to atmospheric deposition of S and N in a dry tropical region. Pedobiologia (Jena) 48:305–311. https://doi.org/10.1016/j.pedobi.2004.03.003

Singh R, Singh MP, Singh AP (2014) Ozone forming potential of tropical plant species of the Vidarbha region of Maharashtra state of India. Urban For Urban Green 13:814–820. https://doi.org/10.1016/j.ufug.2014.05.007

Sukitpaneenit M, Kim Oanh NT (2014) Satellite monitoring for carbon monoxide and particulate matter during forest fire episodes in Northern Thailand. Environ Monit Assess 186:2495–2504. https://doi.org/10.1007/s10661-013-3556-x

Sumit K, Devara PCS, Manoj MG (2012) Multi-site characterization of tropical aerosols: implications for regional radiative forcing. Atmos Res 106:71–85. https://doi.org/10.1016/j.atmosres.2011.11.009

Swamy YV, Venkanna R, Nikhil GN et al (2012) Impact of nitrogen oxides, volatile organic compounds and black carbon on atmospheric ozone levels at a semi Arid Urban Site in Hyderabad. Aerosol Air Qual Res 12:662–671. https://doi.org/10.4209/aaqr.2012.01.0019

Tian D, Niu S (2015) A global analysis of soil acidification caused by nitrogen addition. Environ Res Lett 10:24019. https://doi.org/10.1088/1748-9326/10/2/024019

Tiwari S, Srivastava AK, Bisht DS et al (2009) Black carbon and chemical characteristics of PM10 and PM2.5 at an urban site of North India. J Atmos Chem 62:193–209. https://doi.org/10.1007/s10874-010-9148-z

Trivedi S, Agrawal M (2003) Air quality status in Varanasi City. J Environ Stud Pol 6(2):75–84

Vadrevu KP, Ellicott E, Giglio L et al (2012) Vegetation fires in the himalayan region – Aerosol load, black carbon emissions and smoke plume heights. Atmos Environ 47:241–251. https://doi.org/10.1016/j.atmosenv.2011.11.009

Valdés Manzanilla A, de la Cruz Uc X (2015) Spatial distribution of SO2 concentration and population exposure in the tropical city of Villahermosa, Mexico. Air Qual Atmos Health 8:321–329. https://doi.org/10.1007/s11869-014-0273-8

Vasconcellos PC, Souza DZ, Magalhães D, Da Rocha GO (2011) Seasonal variation of n-alkanes and polycyclic aromatic hydrocarbon concentrations in PM10 samples collected at urban sites of São Paulo State, Brazil. Water Air Soil Pollut 222:325–336. https://doi.org/10.1007/s11270-011-0827-4

Verma A, Singh SN (2006) Biochemical and ultrastructural changes in plant foliage exposed to auto-pollution. Environ Monit Assess 120:585–602. https://doi.org/10.1007/s10661-005-9105-5

WHO (2016). Ambient air pollution database. http://www.who.int/entity/phe/health_topics/outdoorair/databases/who-aap-database-may2016.xlsx?ua=1. Accessed 26 June 2017

Wickramasinghe AP, Karunaratne DGGP, Sivakanesan R (2011) PM10-bound polycyclic aromatic hydrocarbons: concentrations, source characterization and estimating their risk in urban, suburban and rural areas in Kandy, Sri Lanka. Atmos Environ 45:2642–2650. https://doi.org/10.1016/j.atmosenv.2011.02.067

Xiankai L, Jiangming M, Shaofeng D (2008) Effects of nitrogen deposition on forest biodiversity. Acta Ecol Sin 28:5532–5548. https://doi.org/10.1016/S1872-2032(09)60012-3

Yerramsetti VS, Gauravarapu Navlur N, Rapolu V et al (2013) Role of nitrogen oxides, black carbon, and meteorological parameters on the variation of surface ozone levels at a tropical urban site – Hyderabad, India. Clean Soil Air Water 41:215–225. https://doi.org/10.1002/clen.201100635

Zvereva EL, Toivonen E, Kozlov MV (2008) Changes in species richness of vascular plants under the impact of air pollution: a global perspective. Glob Ecol Biogeogr 17:305–319. https://doi.org/10.1111/j.1466-8238.2007.00366.x